

UCD CENTRE FOR ECONOMIC RESEARCH

WORKING PAPER SERIES

2006

Measuring Fuel Diversity in Power Generation

Colm McCarthy and Jeremiah O'Dwyer, University College Dublin
and
Richard Troy, Electrotec

WP06/18

November 2006

**UCD SCHOOL OF ECONOMICS
UNIVERSITY COLLEGE DUBLIN
BELFIELD DUBLIN 4**

DRAFT, comments invited

Measuring Fuel Diversity in Power Generation

Colm McCarthy (University College Dublin)

Jeremiah O'Dwyer (University College Dublin)

Richard Troy (Electrotec)

November 2006.

colm.mccarthy@ucd.ie

1. Introduction

The extent of input substitution possibilities in production, including fuel substitution possibilities in power generation and in other heavy industries, is most often measured through econometric estimates of own- and cross-price elasticities, either from time-series for whole industries or from plant-level data, using translog and other popular specifications. The resultant estimates are model and sample dependent, and tend to vary widely from one study to the next. See for example Soderholm (2000), who reports strong short-term fuel substitution for Western Europe as a whole, or Tauchmann (2006), who reports low short-run elasticities for the German power sector.

But even if reliable sets of elasticities could readily be computed, they are not easily interpreted in the terms of most immediate appeal, such as an answer to the question 'How flexibly does total system cost respond to a specific price shock?' In addition to traditional econometric estimates of own- and cross-price elasticities, several specific *ad hoc* measures of fuel diversity, in the overall fuel mix and in power generation systems, have been suggested, designed to reflect positively a greater spread of fuel types. But these are statistical measures which lack an obvious economic interpretation.

2. Sources of Fuel Diversity in Power Generation

Power stations have design lives of 25 years and upwards. In a large system, roughly 3% of capacity will get replaced or life-extended each year, and in many European countries perhaps another 2% gets added to accommodate demand growth. Over any reasonable time horizon, the system thus gets progressively replaced at the rate of maybe 5% per annum, and choices about fuel type for the new stations get embedded in the technology. In recent years, after a long period where gas was the fuel of choice in Europe for newbuild capacity, resulting in a steady increase in gas reliance, attention is beginning to focus away from gas and onto nuclear, coal and renewables, in response to dramatic increases in fossil fuel prices, including sharp movements in their relative prices. This trend has also been propelled by the introduction of the EU's ETS (Emissions Trading Scheme) of tradeable permits for carbon emissions, which has further increased the marginal cost of generation from fossil fuels and affected their relative cost; and concerns about Europe's exposure to Russian market power in gas supply.

There could be substantial changes in the composition by fuel of Europe's powergen capacity over the next couple of decades, as indeed there has been historically over similarly long periods. But for the time being, and given that the minimum planning and construction horizon for new stations is five or six years, the distribution of capacity by fuel type is predetermined.

But even over the short run, there can be substantial fuel substitution possibilities in power generation, for two reasons. These are the presence of dual- or multi-fired stations on the system, for example stations which can run on oil or gas, and the pronounced intra-day and seasonal variation in load, which means that there is an hour-by-hour choice as to which stations to run.

A system with a range of stations using different fuels can thus respond, even in the short run, to changes in relative fuel prices. Of the two effects, the second will tend to be the most powerful for many systems: peak-to-through ratios in power demand can be of the order of three to one, which implies that for most hours of the year, there can be a choice between fuel types. Dual firing of power stations is however not very widespread.

3. Measures of Fuel Diversity

With $Q = Q(F)$ (1)

where Q is output and F a vector of factor and/or raw material inputs, it is natural to ask how much flexibility is available to the industry in responding to variations in the relative prices of the elements of F . In the powergen context, capital stock is fixed in the short-run, and labour costs are immaterial, so the elements of F are just quantities of the different fuel types. Moving from the vector P_0 of input costs to a new vector P_1 while maintaining output at Q_0 will involve a new (minimum) cost level, and a new combination of fuel inputs F_1 which may differ from F_0 unless the relative prices of the fuel inputs are unchanged.

Several purely statistical indices have been proposed to measure the diversity of fuel inputs in the power generation context. These include

(i) C_1 , the share of the largest fuel relied upon. This can be measured as either the share of that fuel in actual base output or in industry capacity, more often the latter. The measure is analogous to a concentration ratio in industrial organisation, namely the share of the largest player, and is routinely cited in popular discussion of gas dependence, for example.

(ii) SW, the Shannon-Wiener Index, defined as

$$SW = -\sum W_i \cdot \ln W_i \quad (2)$$

where the W_i is the weight of each fuel in the total. This measure, which has origins in the informatics literature, was first proposed as a measure of fuel diversity in a widely-cited paper, Stirling (1994). Tirole (1988) calls this the Entropy Index, in the context of industry market shares.

(iii) Herfindahl Index,

$$H = \sum w_i^2 \quad (3)$$

the sum of squares of the weights, and also familiar from the industrial organisation literature.

These indices are open to the criticism that they constitute 'answers without questions', Afriat's (1977) dismissal of statistical price index numbers. Economists have, in demand analysis, stressed the superiority of 'true' cost-of-living indices, which answer the following question: How much does it cost, at the new prices, to attain the maximum utility level that could be afforded at the old? The answer to this question clearly depends on the substitution possibilities present in the system of demand (or cost) equations, or equivalently in the structure of preferences in the consumer demand context, the structure of the production technology in the present context.

(iv) An Alternative Diversity Measure: the Bias in the Laspeyres Index

By analogy with the construction of 'true' cost-of-living indices, we can ask: How much does fuel cost the powergen industry at the new prices to generate the same output as was generated at the old? If we call this the True cost index, as with demand analysis, we know that the upper bound (the worst that can happen) is given by the Laspeyres Index. The amount by which the True index falls short of the Laspeyres index, called the Bias of the Laspeyres index in demand analysis, suggests itself as an alternative measure of fuel diversity. Thus with Q held constant, if

$$\text{the Laspeyres Index } L = \sum P_1 F_0 / \sum P_0 F_0, \quad (4)$$

$$\text{the True Index } T = \sum P_1 F_1 / \sum P_0 F_0, \quad (5)$$

$$\text{and the Bias Index (of Diversity)} = 100(1-(T-1)/(L-1)) \quad (6)$$

This is an indicator of diversity in fuel choices in the following sense. The Bias index will equal zero where the True and Laspeyres indices coincide. In the current context, this can be thought of as zero fuel diversity. The technology of production is such that there is no scope to substitute away from inputs (fuels) which are becoming relatively more expensive. The Bias index would attain a maximum of unity in the (perhaps far-fetched) case where the True index does not change at all in the face of the new relative price vector, which would correspond to n-1 prices unchanged, and the nth higher-priced input completely substitutable by one, or a combination, of the others.

As with the analogue in consumer demand analysis, the True index and hence the Bias index of substitution possibilities will depend on the P_0 and P_1 price vectors, as well as on the structure of preferences (or production technology as the case may be). Estimates of bias in consumer price indices tend to be small, at least at aggregation levels of eight or ten commodity groups, but this is because the P_0 and P_1 price vectors tend not to differ greatly. They can differ enormously with powergen fuels.

The superior interpretability of the Bias index is purchased at a cost, in comparison to the statistical indices, which can easily be computed from market share data. As with True indices in consumer demand, where consumer response to price changes must be modelled, the system's response to changes in input costs must be known. Thus if a Bias index were to be employed as a kind of generalised summary measure of the substitution elasticities in production, the parameters of the system must be estimated. The Bias index can then be computed for any pair of price vectors. It turns out to be straightforward, in the power generation case, to directly simulate the impact of changes in fuel costs on fuel demand for any hypothesised load including a constant load, through the device of a *merit-order dispatch model*. The critical ingredients are knowledge of each power station, its fuel type, dual-fueling if applicable, conversion efficiency rating and availability; and knowledge of the hourly pattern of demand for all 8,760 hours of the reference year. Given the carbon content of each fuel, as well as carbon and fuel price assumptions, the behaviour of the system can now be simulated.

Stations will be dispatched in *merit order*, that is, those with lowest fuel costs are dispatched first. Virtually all short-run marginal costs in powergen are fuel costs. Merit order dispatch can be thought of as either the rational cost-minimising behaviour of a monopolist, or following Stoft (2002) as an efficiency condition in the design of a competitive power market.

Since the merit order tends to produce a strict ranking for given fuel prices, there will be price changes too small to alter the dispatch priority, and over these ranges, the Bias index will be zero, and there is no diversity. But when prices change substantially, there can be sharp reversals in merit order, huge changes in optimal fuel inputs, and a substantial Bias in the Laspeyres index, indicating effective fuel diversity.

4. Short-Run Fuel Diversity in the Republic of Ireland System

The dispatch model has been run for the 2005 load pattern, with the list of stations actually available throughout that year in the Republic of Ireland system. New stations now on load (Tynagh, a gas station, and West Offally, a peat station) are not included. There is one dual-fired station, Poolbeg (gas or HFO), and it is entered twice, with the restriction that both 'stations' cannot run simultaneously. The pumped storage facility at Turlough Hill is ignored, since it is not actively dispatched but rather is held as spinning reserve. All renewables, which have zero fuel cost are treated as base load and dispatched evenly through the year, which is adequate for present purposes. In reality, availability of these units is stochastic, in the case of wind, and is actively managed in the case of conventional hydro.

The two principal price vectors of interest are shown in the table.

Table 1: Powergen Fuel Prices, December 03 and December 05, €per MWhr.

	Price Dec 03	Price Dec 05	% Change
Coal	3.93	5.85	+48.9
Gas	12.01	32.19	+168.0
HFO	14.43	22.36	+55.0
Gasoil	33.21	41.78	+25.8
Peat	11.34	14.79	+30.4
Renewables	0.00	0.00	

Source: Electrotec

Not merely have there been sharp increases in all fuel sources, there have also been dramatic changes in relative prices. The relative price of gas, the most important fuel source in Ireland, rose fastest of all between December 2003 and December 2005.

The dispatch model (see appendix) was programmed at both price vectors to select the cost-minimising fuel combination for the same 2005 load curve, ignoring for the moment the introduction of the carbon regime from January 2005. Gasoil, used only for emergency generation, is not dispatched. The results, expressed as % of electrical energy sent out, were

Table 2: Dispatch by Fuel at 03 and 05 Prices, Carbon Charge = 0.

Fuel	at 03 Prices	at 05 Prices	% Change
Coal	24.8	24.8	-
Gas	55.5	27.6	-50.3
HFO	1.8	27.3	+ 1448.8
Renewables	9.0	9.0	-
Peat	9.0	11.4	+26.3
Total	100.0	100.0	-
Laspeyres Index	1.00	2.30	+130
True Index	1.00	2.07	+107

Gas share collapses, to be replaced with HFO. Fuel costs would have risen by 130% if there were no substitution possibilities. With merit order dispatch, they rise only 107%. The difference in cash is €124m. for a full year. If gas had risen a little faster, by 190% to €34.83, with all other prices constant, the substitution impact is even more dramatic. The Laspeyres index goes to 205, but the true index to only 151.

Note that any of the statistical indices would show low fuel diversity readings at the 03 prices, given the high gas weight. But it is precisely this high initial gas weight that makes the True index rise by less than the Laspeyres index. . At the 05 prices, the statistical indices would indicate a more diversified fuel balance. But the exposure to a gas price rise is now *greater*, since there is less possibility to substitute away from gas. Equivalently, the non-gas capacity is now being dispatched, and a further sharp rise in gas price just has to be borne. The system moves to a fixed-coefficients world eventually as gas price rises, and there is *less*, not more, fuel diversity.

In assessing short-run fuel diversity in the face of specific hypothetical price changes, there appears to be no alternative to simulating the system's behaviour, and indices based on initial market shares (whether of fuel burn or of capacity) are likely to be misleading.

If we hold all other fuel prices fixed, and vary only the gas price with no carbon charge, this is what happens.

Table 3: Response to Gas Price Changes, 2003 Price Base, Carbon Charge = 0

Gas Price €	Gas % Elec Sent Out	True Index	Laspeyres Index
10.21	61.0	0.889	0.895
12.01 (Actual 03)	55.5	1.000	1.000
15.01	45.4	1.16	1.18
19.82	37.3	1.34	1.46
25.22	16.0	1.44	1.77
30.03	16.0	1.51	2.05
34.83	16.0	1.58	2.33

Above a certain point, a minimum of gas plant *must* be dispatched, since there is nothing else available. From this point onwards, there is no effective fuel diversity in the face of a further gas price rise. (Note that the expenditure weight of gas does not coincide with the % gas in electricity sent out in the above table: it will rise with the gas price).

5. The Impact of the Carbon Charge

Since January 2005, generators must take account of the cost of carbon emissions. The EU system allocates permits to various heavy industries, principally powergen but the system also covers steel, cement, glass, brick, pulp and paper. Permits can be traded, and all those covered must have sufficient permits to cover their actual emissions for the three-year period 2005 to 2007. The marginal cost of power generated now includes the cost of carbon. (See Newbery (2006) for a critique of the system, on the grounds that it shifts demand toward gas, enhancing the market power of Russia, to a greater extent than would a carbon tax).

The different fuels have differing carbon content. It is zero for renewables and nuclear, whose economics will be greatly improved if carbon charges are high. Gas has lower carbon content than HFO, lower in turn than coal, with peat worst of all.

Table 4: The 2003-Price Dispatch at Varying Carbon Charges.

€	Gas %	Coal %	HFO %	Peat %	Renew %
Carbon = 0	55.5	24.8	1.8	9.0	9.0
Carbon = 10	59.4	24.8	1.8	5.0	9.0
Carbon =15	61.0	24.4	1.8	3.8	9.0
Carbon = 20	61.5	23.9	1.8	3.8	9.0
Carbon = 25	62.9	22.6	5.3	0.2	9.0
Carbon =30	67.7	18.0	5.3	0.0	9.0
Carbon =35	67.7	18.0	5.3	0.0	9.0

At the low gas prices prevailing, gas moves up the merit order with the carbon charge. Coal suffers, as does peat. Interestingly, it is HFO that plugs the gap at these 2003 prices. Renewables are dispatched at maximum even with no carbon charge.

These patterns of carbon charge impact reflect the initial prices assumed. A further set of simulations was run with the (much higher) 2005 prices.

Table 5: The 2005-Price Dispatch at Varying Carbon Charges

€	Gas %	Coal %	HFO %	Peat %	Renew %
Carbon = 0	27.6	24.8	27.3	11.4	9.0
Carbon = 20	37.5	24.8	17.6	11.2	9.0
Carbon = 40	43.0	24.8	14.3	9.0	9.0
Carbon = 50	43.9	24.4	22.3	0.4	9.0
Carbon = 55	49.4	24.4	16.8	0.4	9.0
Carbon = 60	49.9	23.9	16.8	0.4	9.0
Carbon = 65	49.9	23.9	16.8	0.4	9.0

Even at recent high gas prices, the gas share recovers substantially as the carbon charge rises. Coal does not suffer, but if carbon goes to very high prices, peat is wiped out. HFO remains in the mix, even at high carbon prices.

References:

Afriat, Sydney (1977): *The Price Index*, Cambridge, Cambridge University Press.

Newbery, D. (2006): Climate Change and its Effect on Market Power in the Gas Market, mimeo, University of Cambridge Working Papers.

Soderholm (2000): Fuel Flexibility in the West European Power Sector, *Resources Policy* 26, pgs 157-170, 2000.

Stirling, A. (1994): Diversity and Ignorance in Electricity Supply Investment, *Energy Policy*, pgs. 195-216, March 1994.

Stoft, Steven (2002): *Power System Economics*, WHey Interscience.

Tauchmann (2006): Firing the Furnace? An Econometric Analysis of Utilities' Fuel Choice, *Energy Policy*, forthcoming.

Tirole, J. (1988): *The Theory of Industrial Organisation*, MIT Press, Cambridge, Mass., 1988.

Gas Price Sensivity Analysis

Exercise 1

Assumptions

- Base fuel prices are taken as the actuals prevailing at Dec 2003
- The Dispatch Model was run for a range of gas prices 15% below the 2003 actual to almost three times that level (see table on the right)
- The resulting change in merit order dispatch is shown in Chart A
- The resulting change in the average cost of the 'sent-out' unit of electricity is shown in Chart B

2003	€/ MWhr
Coal	3.93
Gas	12.01
HFO	14.43
Gas Oil	33.21
Peat	11.34

Gas	Incr
12.01	
10.21	-15.0%
12.01	0.0%
15.01	25.0%
19.82	65.0%
25.22	110.0%
30.03	150.0%
34.83	190.0%

CHART A

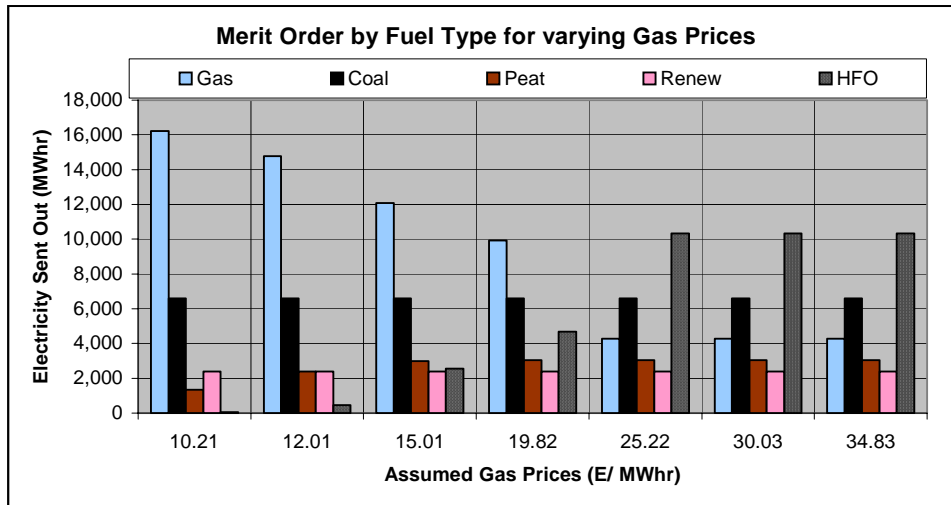
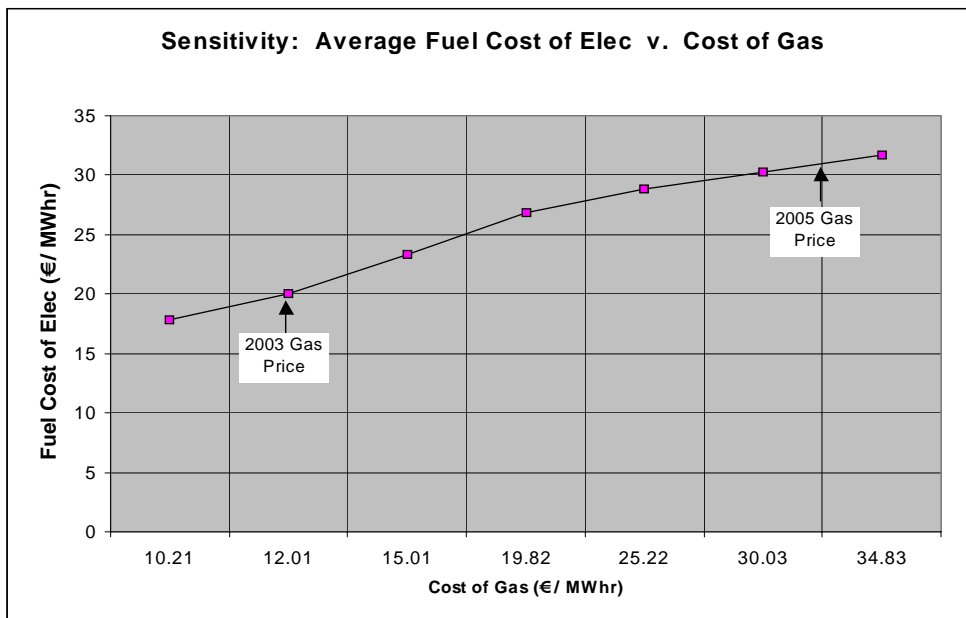


CHART B



Gas Price Sensivity Analysis

Exercise 2

Assumptions

- Base fuel prices are taken as the actuals prevailing at Dec 2003 – Table A
- We know from Table B how much CO₂ is generated by each fuel
- We can, therefore, calculate the impact of CO₂ surcharges on each fuel as shown in Table C
- The Dispatch Model was run with each fuel priced in this way.
- The resulting change in merit order dispatch is shown in Chart A
- The resulting change in the average cost of the ‘sent-out’ unit of electricity is shown in Chart B

A

2003	€/ MWhr
Coal	3.93
Gas	12.01
HFO	14.43
GasOil	33.21
Peat	11.34

B

	Tonns CO ₂ / GJ	€/ GJ
Coal	0.0970	22.70
N. Gas	0.0573	13.40
HFO	0.0764	17.87
Gas Oil	0.0737	17.24
Peat	0.1060	24.80

C

CO ₂ Surch	Gas	Coal	HFO	Peat
E / Tonne	E / MWhr	E / MWhr	E / MWhr	E / MWhr
10	16.13	10.91	19.93	18.97
15	18.20	14.40	22.68	22.79
20	20.26	17.89	25.43	26.61
25	22.32	21.39	28.18	30.42
30	24.38	24.88	30.93	34.24
35	26.44	28.37	33.68	38.05

CHART A

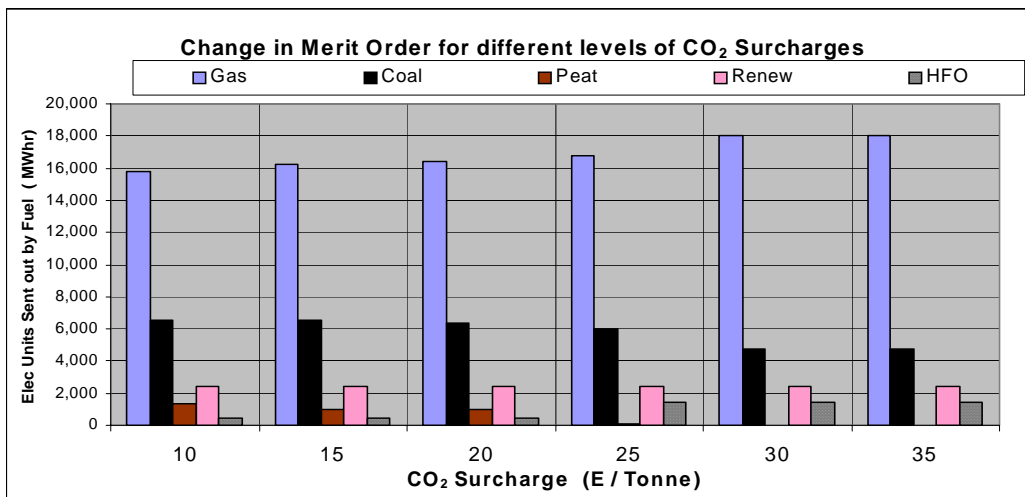
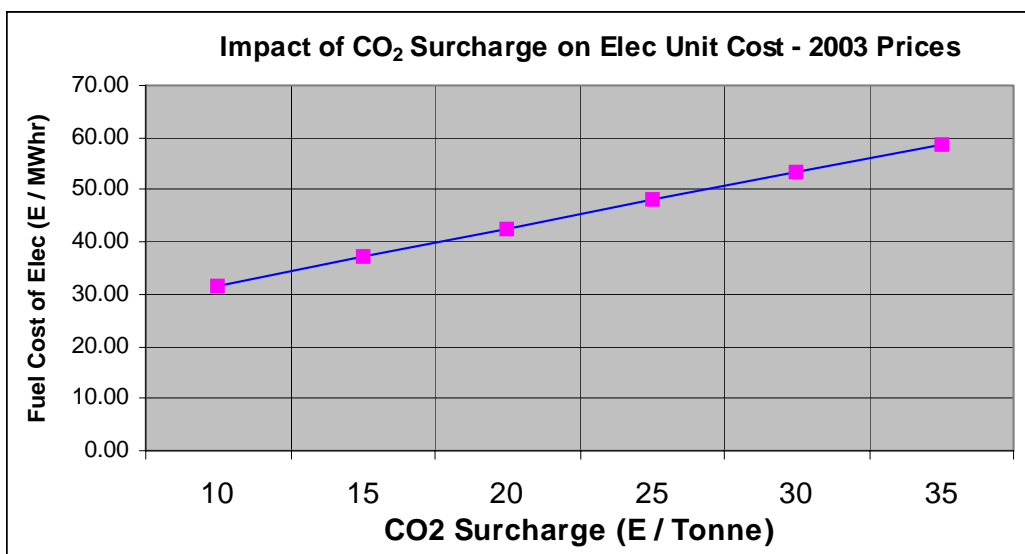


CHART B



Gas Price Sensivity Analysis

Exercise 3

Assumptions

- Base fuel prices are taken as the actuals prevailing at Dec 2005 – Table A
- The impact of CO₂ surcharges on each fuel as shown in Table B
- The Dispatch Model was run with each fuel priced in this way.
- The resulting change in merit order dispatch is shown in Chart A
- The resulting change in the average cost of the ‘sent-out’ unit of electricity is shown in Chart B

A

2005	E / MWhr
Coal	5.85
Gas	32.19
HFO	22.36
GasOil	41.78
Peat	14.79

B

CO ₂ Surch	Gas	Coal	HFO	Peat
E / Tonne	E / MWhr	E / MWhr	E / MWhr	E / MWhr
20.00	40.43	19.82	33.35	30.06
40.00	48.68	33.79	44.35	45.32
50.00	52.80	40.77	49.85	52.95
55.00	54.86	44.26	52.60	56.77
60.00	56.92	47.75	55.35	60.59
65.00	58.98	51.25	58.10	64.40

CHART A

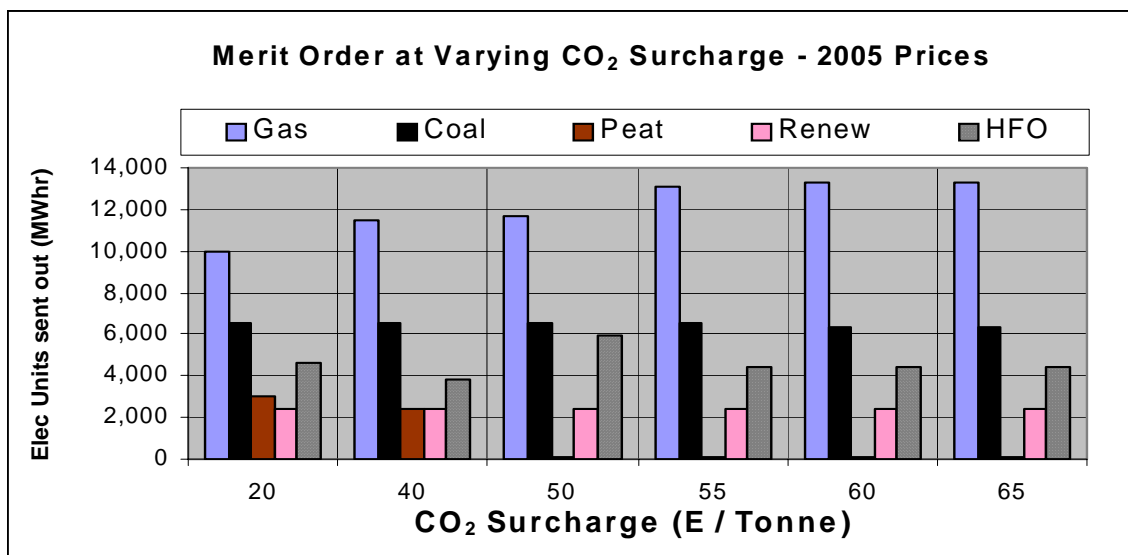
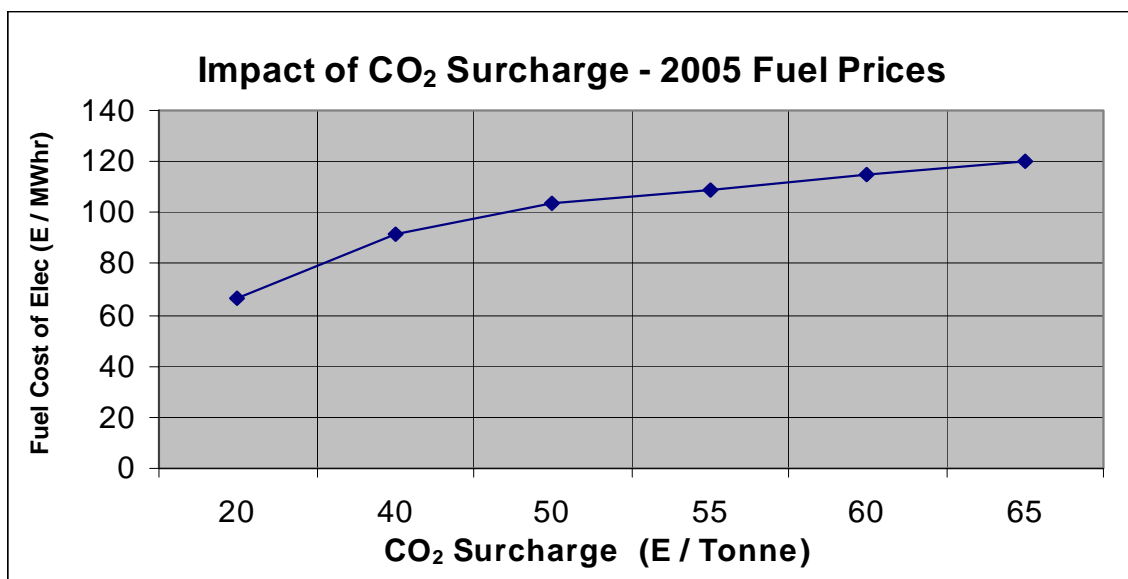


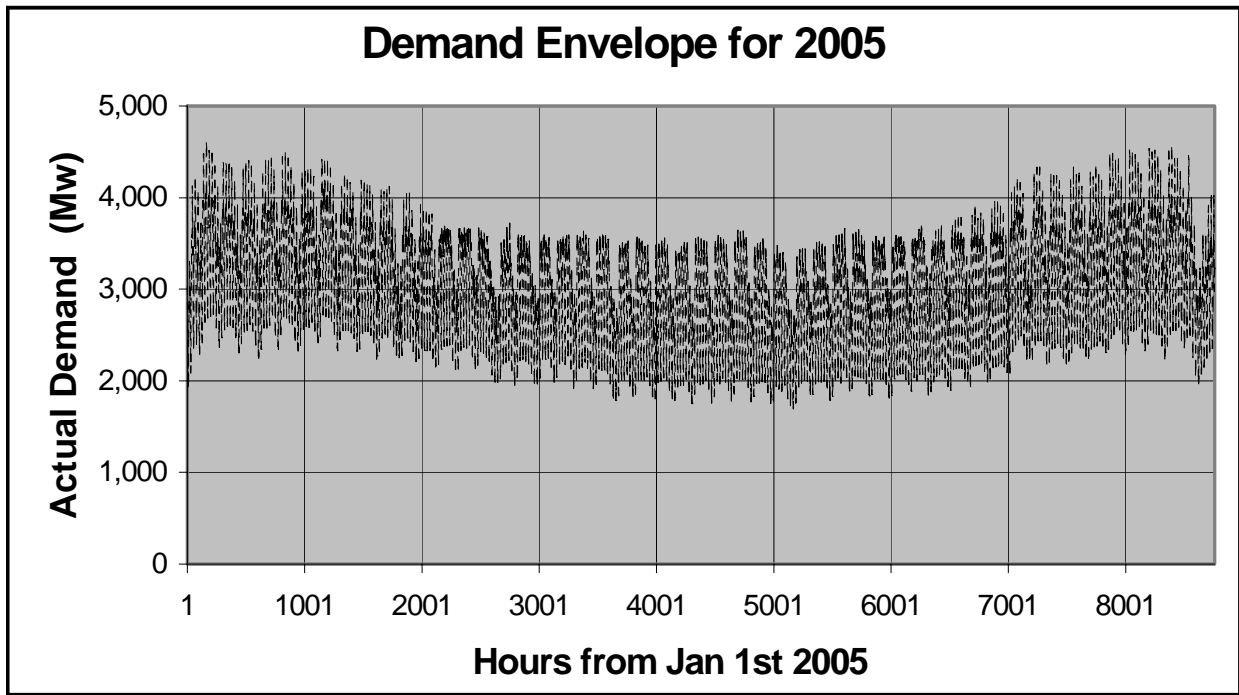
CHART B



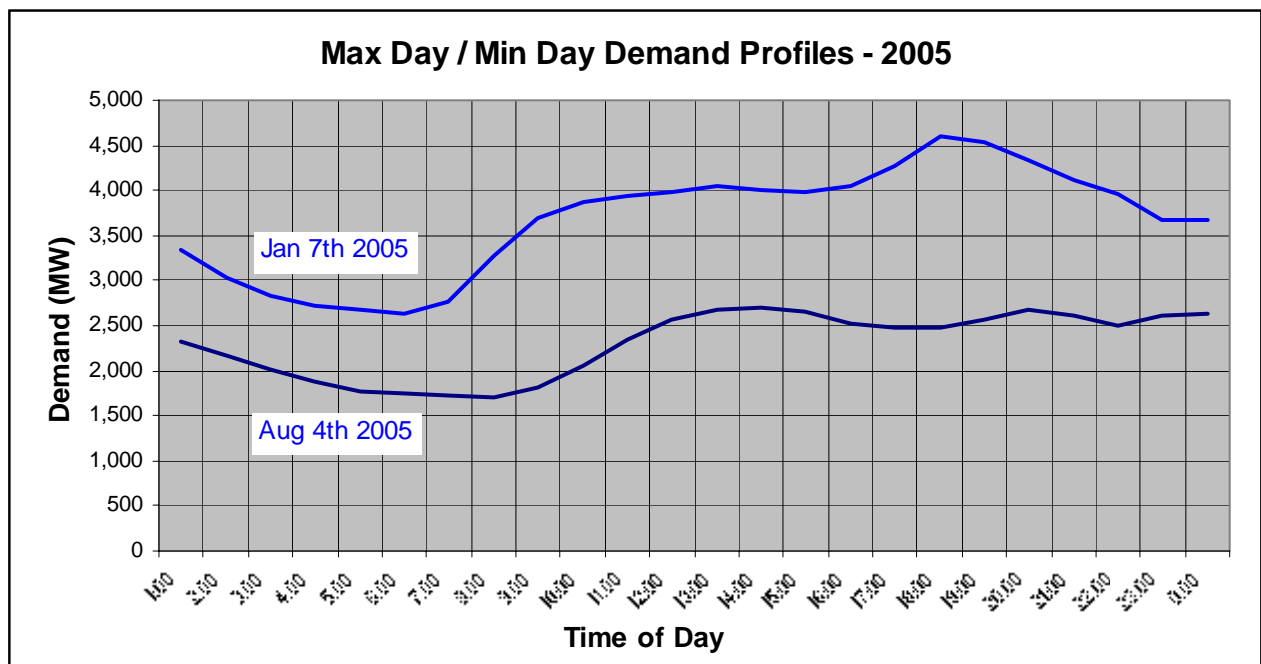
Gas Price Sensivity Analysis

Exercise 4

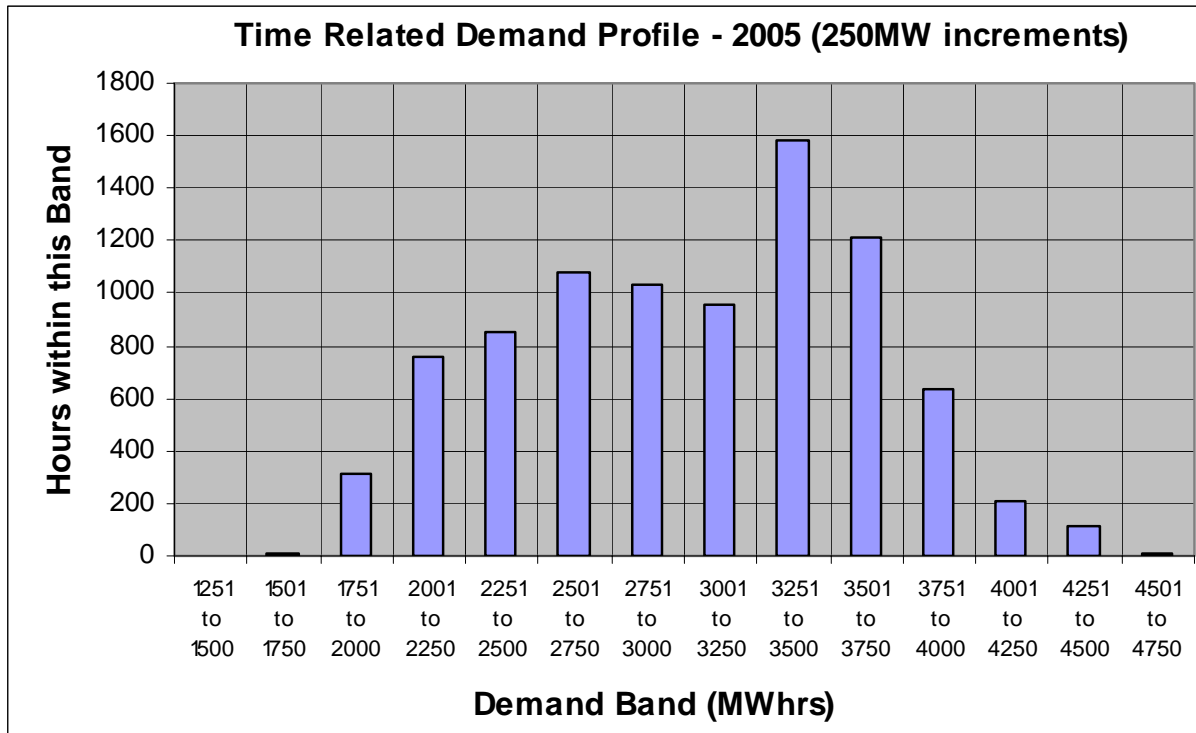
Time Related Demand Patterns



Max/Min Day Demand Patterns



Time Duration by Dispatch Bands



Time Related Demand Profile

